Some indications of a reversed surface flow around Tasmania in the Fine Resolution Antarctic Model (FRAM)

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ABSTRACT

South of Tasmania, the Fine Resolution Antarctic Model (FRAM) shows a narrow band of westward upper layer flow. We argue that this is caused by the closure of the Indonesian passage in FRAM. This is supported by numerical experiments carried out by Hirst & Godfrey (1993). The FRAM surface temperature and salinity distribution exhibits distinct anomalies in the southeast Indian Ocean, in good agreement with anomalies observed in the Hirst & Godfrey (1993) model. Indonesian Throughflow water advects heat into the Indian Ocean; its absence in FRAM results in a lack of thermal energy to warm the Indian Ocean in the model. The surface salinity anomaly is most likely caused by an over-estimated Ekman transport. The weakened heat and salinity transport in FRAM restrict surface convection in the mid-latitude region to approximately 350 m.

The effect of the Indonesian Throughflow closure in FRAM is even more dramatic for the circulation around Australia and Tasmania. Hirst & Godfrey's (1993) results suggest that in the case of an open Indonesian passage, the flow in the surface layer is eastward, ie from the Indian to the Pacific Ocean. FRAM shows westward flow consistant with a closed Indonesian passage.

Introduction

The Fine Resolution Antarctic Model (FRAM) is an eddy resolving model of the circulation of the Southern Ocean. It uses a closed model domain, with the northern boundary placed at 24°S. A closed northern boundary excludes the possibility of net southward transport in the Indian Ocean from the Indonesian Throughflow (and, likewise, net northward transport in the Pacific Ocean). In this note we investigate the effect of the missing throughflow upon sea surface temperature (SST), sea surface salinity (SSS) and the flow pattern for the southeast Indian Ocean. We demonstrate that the absence of the throughflow causes temperature anomalies, weakens convection in regions of Subantarctic Mode Water formation and results in a reversal of the flow around the southeast corner of the Australian continent by comparing the FRAM data with results from the model of Hirst and Godfrey (1993).

The Indonesian Throughflow is an important link in the global thermohaline circulation (Broecker, 1991), allowing flow from the Pacific Ocean into the Indian Ocean north of Australia. It constitutes one of the possible return pathways for North Atlantic Deep Water (NADW) which upwells in the Southern Ocean and into the permanent thermocline of Pacific Ocean. This “warm water route”, in which the return flow is variably estimated between 2 and 16 Sv (Godfrey, in press), is complemented by the “deep water route” from the Pacific into the Atlantic Ocean through Drake Passage (Rintoul,1991). A recent reappraisal of the global thermohaline circulation by Schmitz (1995) presents a synthesis of the available information into a somewhat more complex four-layered system. However, in all concepts of the global thermohaline circulation the Indonesian Passage remains a main pathway for the exchange of thermocline water between the Pacific and Indian Oceans.

Several authors (eg. The FRAM Group, 1991; Saunders & Thompson, 1992; Stevens & Killworth, 1992; Killworth, 1992; Thompson, 1993; Quartly & Srokosz, 1993; Doos & Webb, 1994; Stevens & Thompson, 1994; Feron, 1995; Grose et al., 1995, Lutjeharms & Webb, 1995) have analysed FRAM model data. A detailed description of FRAM can be found in this literature. Analysis so far indicates good agreement between the observational and model data base.

FRAM was primarily developed to investigate the particular dynamics of the Southern Ocean, characterised by high mesoscale eddy activity. The model was integrated for 16 years only, not allowing for large scale changes in the distribution of temperature and salinity. Bottom, deep, intermediate and mode waters, originally prescribed by the climatology, are still present in the FRAM data set at the end of the integration (Webb et al. 1991). Although a large component of the observed dynamics and property distribution within the Southern Ocean is wind-driven, interaction with the thermohaline component of the large scale dynamics does occur. How much a possible misrepresentation of the thermohaline structure effects the overall dynamics within FRAM remains to be investigated.

A major consequence of the Indonesian Passage is the Leeuwin Current along the West Australian coast (eg. Tomczak & Godfrey, 1994). The Leeuwin Current is a narrow current along the continental shelf and therefore can be considered a somewhat localised phenomenon, and its absence in FRAM could be considered a minor irritation. We intend to show here that the absence of the Indonesian Throughflow in FRAM is not restricted to the suppression of the Leeuwin Current but has much further reaching implications for the property distribution and dynamics. It causes anomalies in the temperature and salinity fields, and a possible reversal of the eastward flow from the Great Australian Bight into the Tasman Sea. Some of these observations are seen in numerical experiments by Hirst & Godfrey (1993).

Results

We used the FRMEAN data set supplied by the FRAM group for our analysis of the FRAM temperature and salinity distribution. The data set was obtained as an average of the 72 monthly data sets from FRAM years 11 - 16 (de Cuevas, 1995; pers. comm). In the following, the temperature distribution is discussed first, followed by the salinity distribution and the distribution of convection in mid-latitudinal regions; all are compared with the Levitus (1982) climatology in turn.

Temperature: Figure 1 shows the temperature distribution for the Indian Ocean surface layer south of 24^{o} S from the Levitus data (a) and from FRAM (b); the last panel gives the difference between the two data sets (c). Regions of large differences are found in the Agulhas Current (AC) and Retroflection domain, west of Australia and north of the Subantarctic Front (SAF), and south of Tasmania extending from the Pacific Ocean into the Great Australian Bight westward to approximately 130^{o} E. The anomaly associated with the domain of the AC and Retroflection is most likely a result of the particular nature how FRAM resolves mesoscale activity and maintains frontal gradients that are heavily smoothed in the Levitus data set. In this area, FRAM is generally colder than the Levitus climatology. This feature is not limited to the climatological mean; Lutjeharms & Webb (1995) show a much colder FRAM in a comparison with quasi-synoptic data (their Figure 7) not only in the surface layer but extending into deeper layers as well.

The following discussion concentrates on the two larger scale features in the vicinity of the Australian continent. West of Australia, the FRAM SST is significantly lower than observed in the climatology. South of Tasmania, FRAM SST is higher. This pattern is consistent with results of Hirst & Godfrey (1993), who carried out two experiments with a global ocean circulation model to investigate the effect of the Indonesian Throughflow on the global oceanic circulation. In their experiment 1, the Indonesian Passage was open, allowing for exchange between the Pacific Ocean and Indian Ocean. In their experiment 2, the passage was closed. With a closed passage less heat is transported into the Indian Ocean. Temperatures are lower, in near surface and in deeper layers as well. The SST anomaly is largest west of Australia. This contrasts with an increased SST for most of the Pacific Ocean extending into the Tasman Sea and the Great

Australian Bight. Keeping in mind that FRAM does not include the Indonesian Throughflow, we conclude from the work of Hirst & Godfrey (1993) that the omission of a throughflow domain north of Australia does have a significant impact upon FRAM characteristics. The resulting lowering of SST is not restricted to the Leeuwin Current along the West Australian coast but occurs on a much larger scale.

Figure 1 also shows a negative SST anomaly in the southwestern Tasman Sea extending into the Great Australian Bight to approximately 130^{o} E. This is again consistent with the effect of closing the Throughflow. Hirst & Godfrey (1993) highlight the fact that in the case of a closed Indonesian Passage a complete reversal of the circulation in the Tasman Sea was observed. The velocity field for the surface layer in FRAM, shown in Figure 2, also shows some westward flow around the southeastern part of Australia and a northward flow into the Great Australian Bight, a flow pattern possible consistent with a closed Indonesian Throughflow domain.

Webb et al. (1991) and Killworth (1992) represented the FRAM velocity field by tracking the path of particles over a period of 50 days. The resulting pattern of the FRAM surface circulation shows no eastwest flow around Tasmania; in contradiction to our representation in Figure 2. The most likely cause for this discrepancy is found in the initial position of the particles. No particle was released close enough to the Australian continent to resolve for the eastwest flow around Tasmania.

Salinity: While the absent Indonesian Throughflow is the most likely cause for the observed temperature anomaly in FRAM, its absence does not explain the observed anomaly in salinity. Figure 3 shows the SSS distribution for the Levitus data, the FRAM data, and the difference between the two data sets. Salinities in FRAM are generally lower north of approximately 40^{o} S and larger south of 40^{o} S. Largest anomalies are observed again for the region west of Australia, where the climatology shows a SSS maximum. This dicrepancy could not be reduced by incorporation of the Indonesian Throughflow in FRAM, since the throughflow water is fresher than south Indian Ocean surface water. Rather than increasing salinity, the inclusion of a passage would lower salinity below values already observed for FRAM and thus intensify the anomaly.

The most likely mechanism for the FRAM SSS anomalies is an over-estimation of Ekman transport and the associated Ekman transport divergence in FRAM. Strong Ekman flow transports low salinity water northward, reducing SSS values in the north and in the mid-latitudinal region west of Australia. The northward flow of surface water in the Ekman layer is responsible for upwelling of NADW in the Southern Ocean, so over-estimation of Ekman flow results in an over-estimation of upwelling. Compared to the hydrographic properties of Southern Ocean surface

water or water of the Antarctic region south of the Polar Front, NADW is characterised by both higher salinity and temperature. The increased upwelling therefore increases SSS values in the south.

Compared to climatology, FRAM surface temperatures in higher latitudes are generally lower compared to those of subtropical and tropical latitudes; but slightly increased SST can be observed in the Antarctic Zone (Figure 1c). The northward directed Ekman transport displaces colder water across the ACC toward the temperate latitudes. An over-estimated Ekman flow therefore not only lowers salinity but also temperature and is most likely contributing toward the temperature anomaly southwest of Australia discussed above.

Convection: The motivation for the above analysis of SST and SSS distribution and its anomalies is a closer examination of the processes causing convection in mid-latitudinal regions. The convection which is observed in a band between approximately 35^{o}S and 45^{o}S is often thought of as being correlated with an oceanic heat loss. Hirst & Godfrey (1993) showed that at least for the domain of the Indian Ocean, the convection is dependent on the Indonesian Throughflow as well. Convection is much reduced in the no-throughflow case. Less heat is transported into the Indian Ocean, therefore less heat is available for exchange with the atmosphere reducing surface generated convective overturn. FRAM does not include the

Indonesian Throughflow, and it can be concluded that convection in FRAM in the mid-latitudinal band is much reduced. FRAM convection is shown in Figure 4 with a maximum depth of approximately 350 m, ie bottom of model layer 8.

It is interesting to note that although the correlation of heat loss and convective overturn holds in most areas, some distinct anti-correlation is also evident. For a large region between 30^{o} S to 40^{o}S and 90^{o} to 110^{o}E significant convection actually occurs in a region of oceanic heat gain (see Hirst & Godfrey, 1993). In Hirst & Godfrey (1993), the depeest convection extends into layer 7, but the ocean surface exhibits a heat gain of above 40 Wm^{2} and should gain positive buoyancy. The location of convection in FRAM (Figure 4) indicates that the fast northward directed transport of cold surface water due to Ekman Drift (Figure 2) constitutes a likely second mechanism for the production of negative buoyancy. The instabilities caused by an advection of denser water within the surface layer are adjusted by convection. As discussed above, this process is most likely overestimated in FRAM. The possibility of this mechanism is, however, probably accounting for the discrepancies observed in the Hirst & Godfrey (1993) correlation of heat loss and convection.

Summary and Conclusion

The present analysis strongly suggests the following features for FRAM. Convection in mid-latitudinal regions is too weak, upwelling in the Polar Zone is too strong, the northward Ekman transport is over-estimated, and a reversed flow around the southeast corner of the Australian continent is a result of not including the Indonesian throughflow. The analysis shows that deficiencies in FRAM are not restricted to its hydrological characteristics but also occur in aspects of its dynamics. The FRAM results demonstrate again the importance of the Indonesian Throughflow for the large scale property distribution in the Indian and Pacific Oceans.

In this note, our argument for a reversal of the flow around Tasmania in the FRAM is based on model data only. In a forthcoming paper (Ribbe & Tomczak, 1995), we present strong evidence for an eastward flow around Tasmania. Carbon-14 observations from the Great Australian Bight are closely correlated with carbon-14 observations from the Indian Ocean indicating eastward flow from the Indian Ocean into the Pacfic Ocean.

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Figures

Figure 1: Sea surface temperature, contoured in 1°C intervals. (a) Levitus (1982) climatology; note the slope of the isotherms west of Australia indicating the southward flowing Leeuwin current. (b) FRAM mean SST; note the difference in the slope of the isotherms west of Australia against (a). (c) The difference (a) - (b).

Figure 2: Velocity in the surface layer of the FRAM. Velocity vectors are scaled and not shown for all grid points to reduce the FRAM data density. The representation is only given for qualitative purposes, but note the absence of any southward flow along the west Australian coast.

Figure 3: Sea surface salinity, contoured at 0.2 intervals. (a) Levitus climatology; note the maximum in the centre of the Indian Ocean subtropical gyre. (b) FRAM mean SSS. (c) the difference (a) - (b).

Figure 4: Convection depth (m) in the FRAM as derived from the FRMEAN data set density field.